The Open Cassegrain Antenna: Part II. Structural and Mechanical Evaluation

By W. J. DENKMANN, F. T. GEYLING, D. L. POPE and A. O. SCHWARZ

(Manuscript received May 14, 1965)

The mechanical features of a preliminary concept for an open cassegrain antenna are discussed briefly. In the analysis, emphasis is given to the upper rotating structure, where the major problems are the provision for an efficient back-up structure for the main reflector and the selection of a suitable subreflector support structure. The philosophy and method of approach are described in detail. Representative deflection results are given for both gravity and wind loading. Other mechanical considerations pertinent to this configuration are discussed in general. The structural implications of exposed operation, in particular those due to wind, are considered at some length. The mechanical feasibility of this configuration is demonstrated by the current results.

I. INTROOUCTION

Various mechanical features of the present concept for an open cassegrain antenna are discussed below. The present concept is based on preliminary analysis of some of the problems posed by the unusual geometry and expected applications of the structure. These problems include the inherent asymmetry of the configuration, the need for rigid "external" supports for the subreflector, the design of the slant bearing and slant axis drives, and the desire to terminate the feed horn adjacent to the azimuth axis. The last requirement permits the horn to connect to the stationary communication equipment through a very short length of circular waveguide and rotary joint concentric with the azimuth axis.

An aperture diameter of 56′ was somewhat arbitrarily selected for this design study. An open cassegrain of that size would meet typical requirements for major satellite communication system earth stations.

Fig. 1 is a line drawing of the basic structural configuration that

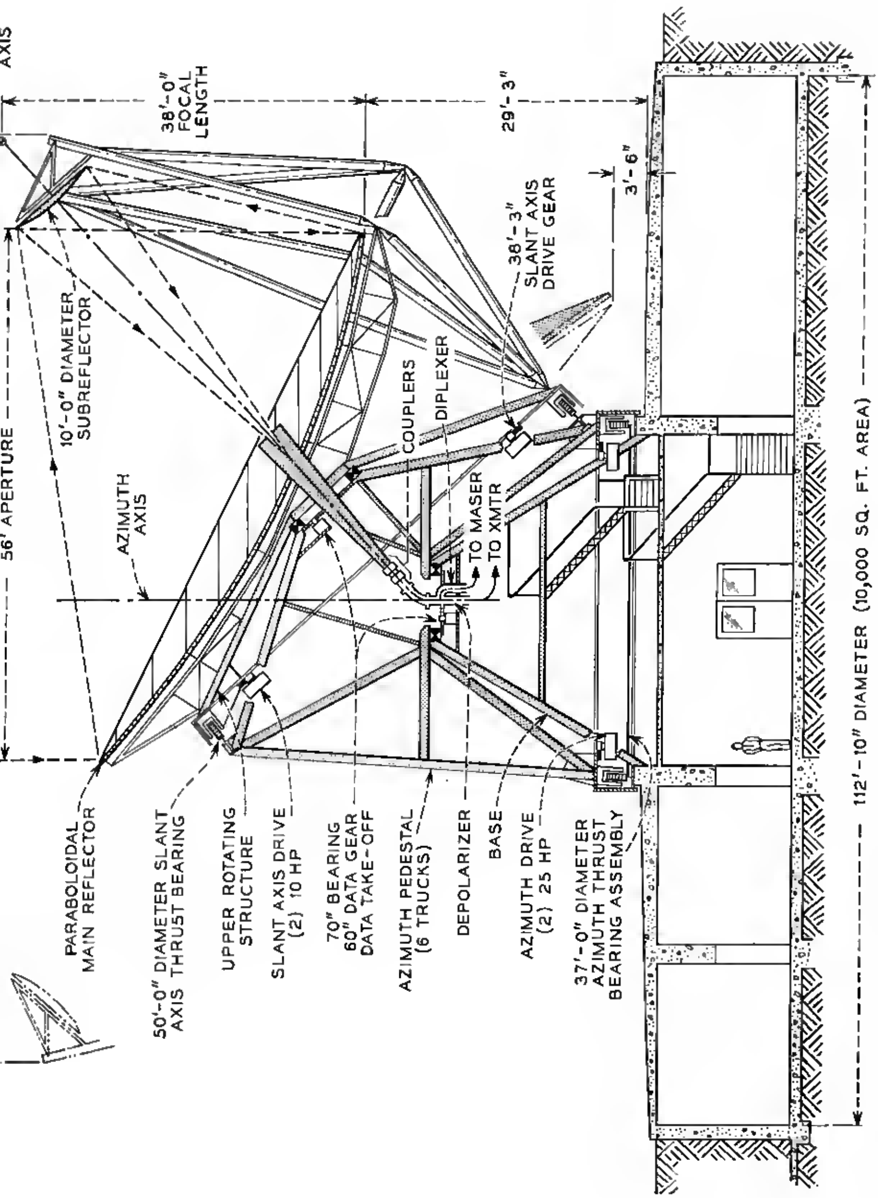

Fig. 1 — Basic layout for the open cassegrain antenna.

emerged from the study. Many of the terms used in the discussion of this configuration are defined in this figure. Fig. 10 further clarifies the geometrical relationship of the structural components and also defines two orthogonal coordinate systems that are referred to in the text.

Dimensions associated with this configuration are:

Aperture Diameter	56 feet
Aperture Area	2460 square feet
Focal Length of Paraboloid	38 feet
Subreflector Diameter	10 feet
Slant Bearing Diameter	50 feet
Azimuth Bearing Diameter	37 feet
Height of Structure	68 feet
Swept Diameter of Structure	96 feet

The slant axis makes an angle of 47.5° with the vertical. This value was chosen to place the minimum elevation 5° below the horizon, which permits easy tracking of the mount at small positive elevation angles. At minimum excursion azimuth and slant-elevation motion are redundant.[1]

Figs. 2, 3, and 4 are photographs of a scale model constructed to aid in the visualization of this concept. This model was also useful in providing a gross understanding of the structural problems and mass distribution. It was discovered, for instance, that rotational stability of the subreflector support structure was far more difficult to achieve than translational stability. The comparatively complex nine-member support grew out of that discovery.

The initial estimates of structural performance were obtained by assuming structural members similar to those used in the horn-reflector antenna at Andover, Maine. The weight of the upper rotating structure is estimated to be 75 tons. The azimuth structure has a weight of approximately 80 tons for a total rotating weight of 155 tons. The polar moment of inertia of the upper rotating structure about the slant axis (I_{zz}) is estimated to be 2.4×10^6 slug-ft^2. The product of inertia of the upper rotating structure (I_{xy}) is approximately 5.2×10^5 slug-ft^2. The polar moment of inertia of the azimuth pedestal alone about the azimuth axis ($I_{z'z'}$) is estimated to be 1.5×10^6 slug-ft^2. Compliances relating the input torque about each axis to the angular response of the rotated structure were also estimated. For the rotation of the upper rotating structure about the slant axis, this figure is 1.5×10^{-10} rad/ft-lb. For the rotation of the total structure about the azimuth axis, the compliance was determined to be 1.9×10^{-10} rad/ft-lb. The

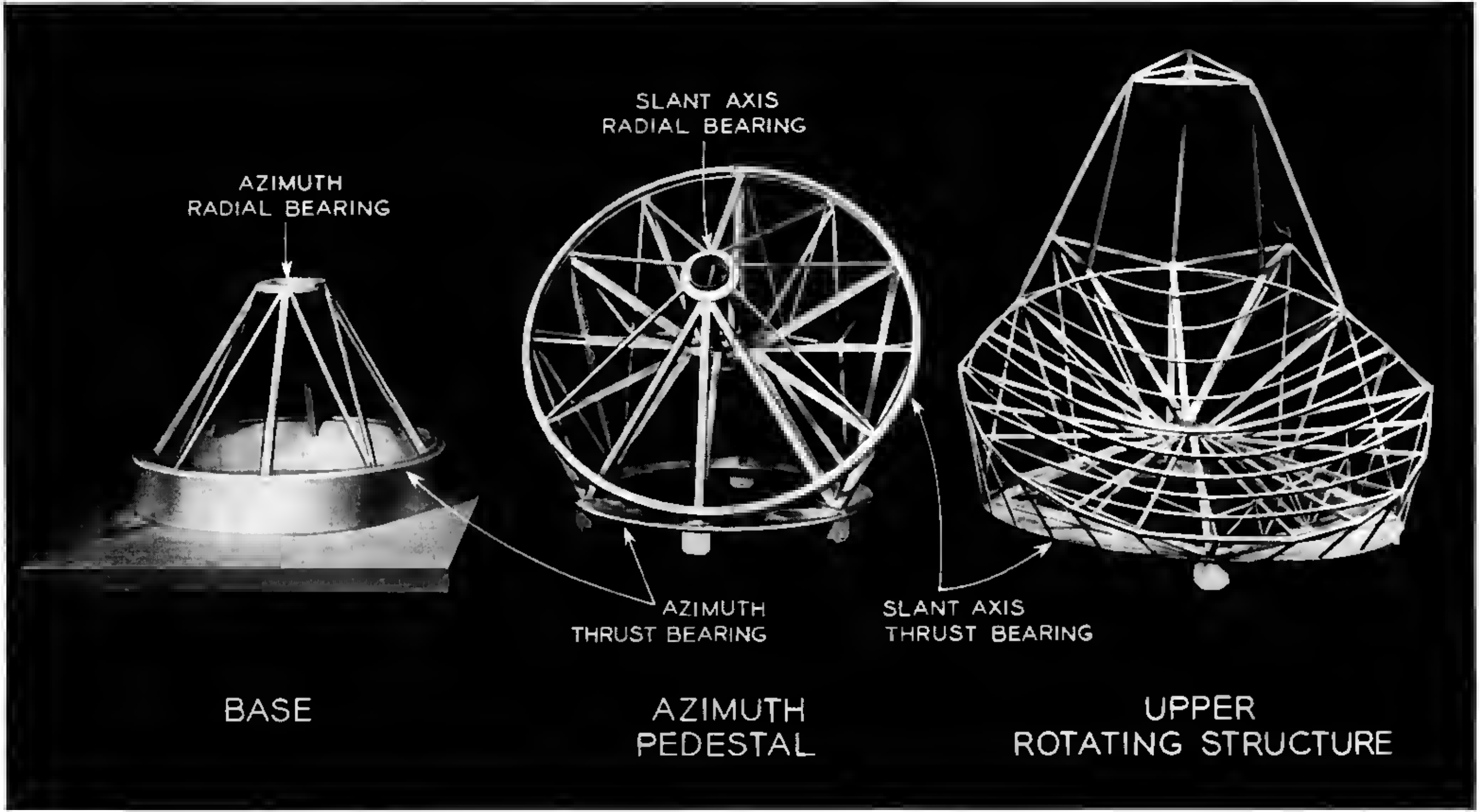

Fig. 2 — Structural components for the open cassegrain antenna.

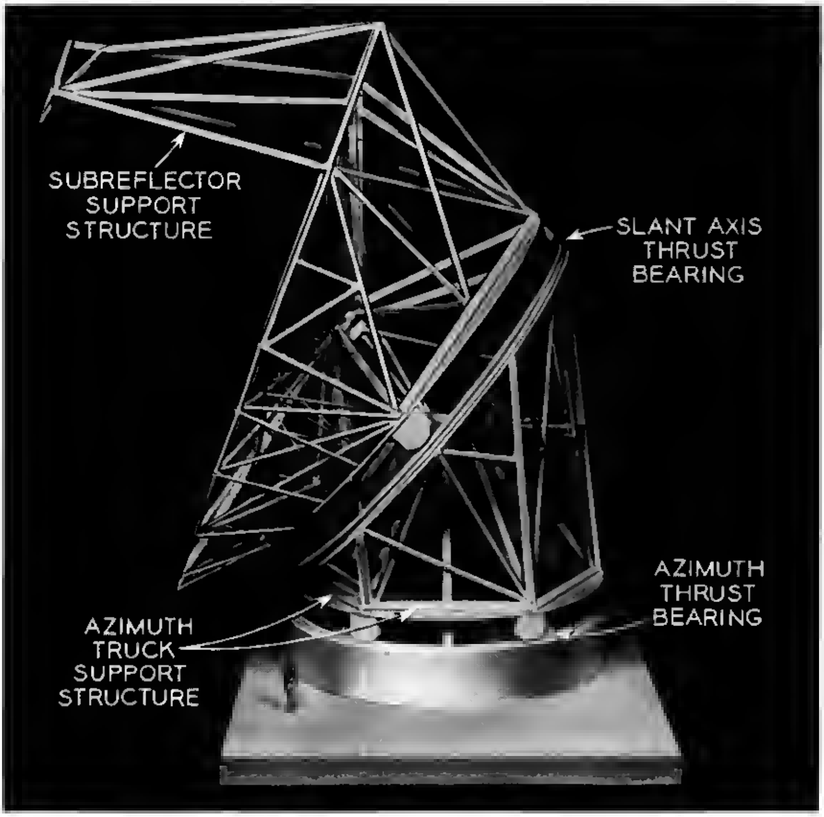

Fig. 3 — Structural components for the open cassegrain antenna assembled.

values of inertias and compliances cited here are necessary for the antenna control system analysis described elsewhere.[1]

II. STRUCTURAL DESIGN

2.1 *Structural Philosophy and Approach*

The open cassegrain configuration has a number of structurally appealing features. For example, the large slant axis bearing is located reasonably close to the reflecting surface. The reflector back-up structure can thus be designed to provide adequate rigidity without excessive weight. The azimuth structure is also compact and lends itself to inherently rigid conventional construction techniques. Provision of

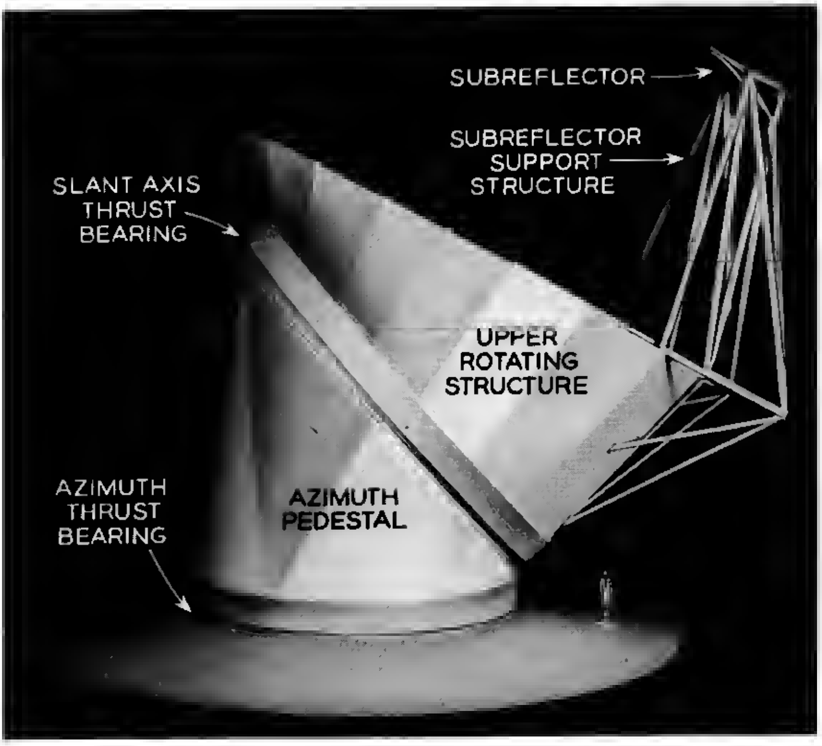

Fig. 4 — Final appearance of the open cassegrain antenna.

radial bearings well above the planes of the corresponding thrust bearings for both axes as shown in Figs. 2 and 5 increases the structure's ability to resist environmental loads. The favorable distribution of resisting forces obtainable with this bearing arrangement accounts for this improvement.

The main structural members of the azimuth pedestal are assumed to be built-up box beams, approximately one-foot square. These are stiffened and interconnected by lighter members. The azimuth pedestal is inherently rigid due to its robust construction and internal structure.

The 37-foot diameter azimuth bearing track supports the weight of the upper rotating structure as directly as possible at the azimuth trucks in an effort to avoid bending loads in this portion of the structure. The azimuth truck support is hexagonal, and is stiffened by a structural ring in the same manner as the slant axis truck support discussed below.

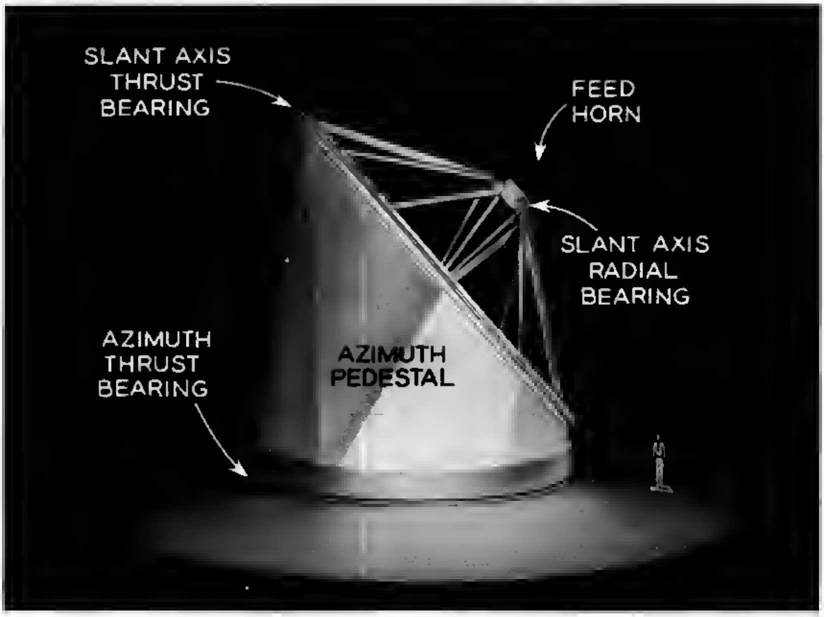

Fig. 5 — Azimuth pedestal of the open cassegrain antenna illustrating elevated radial bearing.

Fig. 3 shows the arrangement of these elements. The structural analysis of the azimuth pedestal, while important, is conventional to the extent that it can be safely assumed that the design can be accomplished in a routine manner at the appropriate time.

The basic structural element in the upper rotating structure is a square frame with bearing trucks at each corner, stiffened by an annular ring member (Fig. 6). The annular ring is shown as a solid section in the model. In practice, the ring would probably be built up in an appropriate manner to provide ample stiffness and backing for bull-gear segments. The slant axis bearing diameter of 50 feet was selected to provide good outboard support for the main reflector.

The reflector back-up structure is assumed to be a pin-jointed space truss for the purposes of analysis. The structural members are thin-walled steel tubes, two to six inches in diameter as the application dictates. The assumption that the joints are ideal, while not realistic, is both conservative and conventional at this stage of the analysis. The curved members crossing the main reflector surface, seen in Figs. 2 and 6, provide points of support for the reflector panels. These members

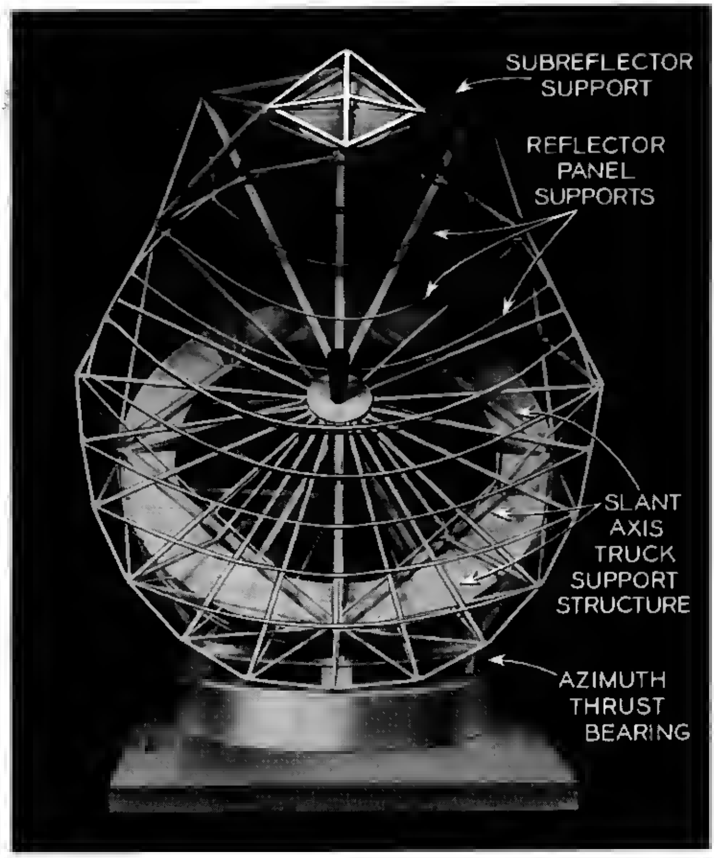

Fig. 6 — Assembled structure of the open cassegrain antenna illustrating slant axis truck support structure and reflector panel supports.

lie along lines of intersection of the reflector surface when the antenna points at zenith and appropriately spaced horizontal planes.

The two major structural problems faced in the configuration are the provision of a sufficiently rigid base for the subreflector support structure, and the design of an efficient back-up structure for the main reflector. These problems were considered early in the study, and a preliminary analysis was made on a variety of suggested structural arrangements. The results of these preliminary analyses were of considerable value for the selection of the structural configuration under discussion.

It is emphasized that the structural configuration, as represented by

the illustrations of the model, is a functional rather than a detailed concept. The described results simply provide a basis for the detailed structural analysis which must follow in the development of a design for construction, and are only indicative of the expected performance of the final structure.

2.2 *Structural Analysis*

Fig. 2 indicates how the structure may be thought of in terms of components. The base, attached to the foundation, provides support for the azimuth bearings and equipment decks. The lower rotating structure, or azimuth pedestal, is composed of two rings, two truncated cones, internal diaphragms, and an enveloping conoidal surface. The upper rotating structure is more complicated, as Fig. 2 shows. The base and the azimuth pedestal are sufficiently simple and straightforward that no unusual problems are anticipated in their design. Hence, subsequent consideration will be given only to the upper rotating structure. For purposes of discussion, this structure is assumed to have rigid support in the plane of the slant axis bearing.

The upper rotating structure is assumed to be composed of a series of radial support trusses extending from the inner cone supporting the slant axis radial bearing outward to the periphery of the main reflector surface. This type of internal stiffening for the main reflector surface is similar to that often used for symmetrical antennas, and proves to be quite efficient in spite of the lack of symmetry of this design. The provision of an adequate support for the subreflector structure can also be incorporated into this arrangement with a minimum of additional complication.

The interaction of the subreflector support structure and main reflector back-up structure has considerable significance for the open cassegrain antenna. Since the subreflector support structure is considerably heavier than a conventional cassegrain support, and since it is located on the edge of the back-up structure rather than centrally, the provision of sufficiently "hard" support points for this structure, is a difficult problem. The elastic behavior of the main reflector back-up structure must be considered in determining subreflector deflections for a given loading. In fact, the deflections of the points of attachment of the subreflector support structure have greater influence on subreflector deflections than the compliance of the support structure itself. For example, preliminary analyses of the subreflector support structure have been carried out with the assumption of complete fixity at the points of attachment. When the compliance of the main reflector

back-up structure was included, the deflections had increased by an order of magnitude over those found in the previous analysis for the same loading. Hence, it was clear that the main reflector back-up structure and the subreflector support structure had to be analyzed as a unit. It was therefore necessary to expand the capacity of existing numerical routines prior to attempting a detailed analysis of the configuration shown.

The structural analysis was done using a general purpose computer program for the solution of three-dimensional trusses developed by one of the authors (W.J.D.). The program is based on the matrix displacement method,[2] suitably modified,[3] to provide sufficient capacity to analyze the reflector back-up structure and the subreflector support structure simultaneously.

Some members in the upper rotating structure carry loads primarily in bending. This is particularly true of the four beams connecting the truck support points. In order to analyze these members with the three-dimensional truss program, the beams were broken up into several hypothetical truss members, and appropriate springs inserted at the nodes to simulate the behavior of the beam. This procedure permits the incorporation of such members into the truss program and predicts their response with satisfactory accuracy.

The loads considered were the dead weight of the structure, including the main reflector panels and the subreflector. The gravity field can be resolved into a component normal to the slant bearing plane and a component tangential to this plane. The effect of the normal component is independent of the rotation about the slant axis and hence complete compensation for these deflections can be accomplished by the final alignment procedure. The changes of the deflections of the reflecting surfaces as the antenna rotates create the difficulties in maintaining surface accuracy at all antenna pointing angles. In this configuration, these changes are due entirely to the component of gravity tangential to the slant bearing plane. Since this component is only 70 per cent of the full gravity load, it should be possible to achieve a reduction in structural weight for the same surface tolerances budgeted to gravity, as compared with a conventional antenna in which the full gravity load influences these changes in deflection.

The deflections of the subreflector and of a number of points on the main reflector surface due to gravity were calculated for both the minimum elevation and the zenith position of the antenna. Knowledge of the deflections due to gravity in two different positions of the antenna is not sufficient to permit their calculation in any position by

simple superposition. The deflections must also be calculated for a third independent position before this procedure can be applied.

Surface deflections were also calculated for a hypothetical wind load calculated from the results of hydrodynamic model testing.[4] A reasonable pressure distribution was assumed to act over the surface of the main reflector. The free parameters of the pressure distribution were adjusted to match statically the torques and resultant forces measured in the laboratory. These pressures were then converted into equivalent static forces at the nodes of the structure, and the resulting deflections calculated. Only one wind loading position was considered, for the antenna pointed at the zenith. A steady 40-mph horizontal wind at an azimuth aspect angle of 60°, (see Fig. 10), was blowing into the concave side of the main reflector. The deflections for this case are plotted in Fig. 7, a contour map of the main reflecting surface as seen looking toward the reflector along the main beam. The

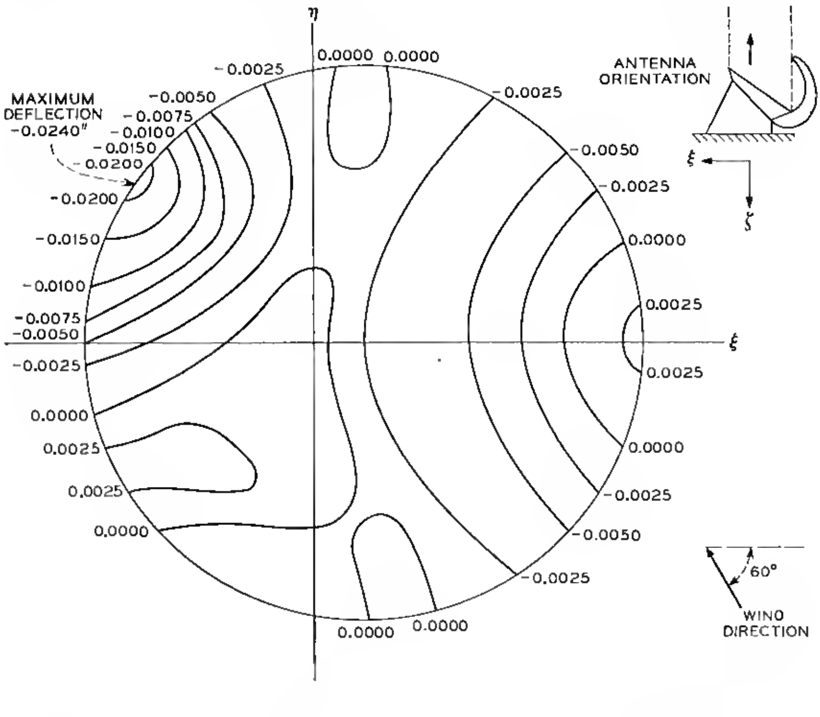

Fig. 7 — Deflections of the main reflector surface in the ζ direction due to a horizontal wind of 40 mph at a wind azimuth aspect angle of 60° (deflections in inches).

deflections shown are parallel to the ζ axis as shown in the figure. The normal and transverse deflections are available, but difficult to present graphically. Fig. 8 is a similar plot of the deflections parallel to the ζ axis due to gravity when the antenna points at zenith. Fig. 9 also shows deflections parallel to the ζ axis due to gravity, but for the antenna at its minimum elevation of $-5°$. The results of these studies reveal a "soft" spot on the periphery of the main reflector. This is immediately evident in Figs. 7, 8, and 9. In subsequent designs, appropriate steps would have to be taken to improve structural rigidity in this region.

Similar results can be superimposed to determine deflections due to combined effects. This would be a task of considerable magnitude. If all aspects of the wind loading are considered, there are four independent variables; the antenna pointing angle (two variables), the wind aspect angle, and the wind velocity. A preliminary study would probably be concerned only with some predetermined maximum operational wind velocity. If the investigation was further restricted to consideration of only the gross aspects of the deflection pattern, such as maximum deflection, or perhaps RMS deflection, it would be well within the scope of current capabilities. "Worst case" combinations of wind and gravity loading for subsequent design purposes could be obtained rapidly using computer techniques. An understanding of the interaction of such loadings would also be obtained.

The selection of an appropriate subreflector support was difficult. This component must be sufficiently rigid for all loading conditions,

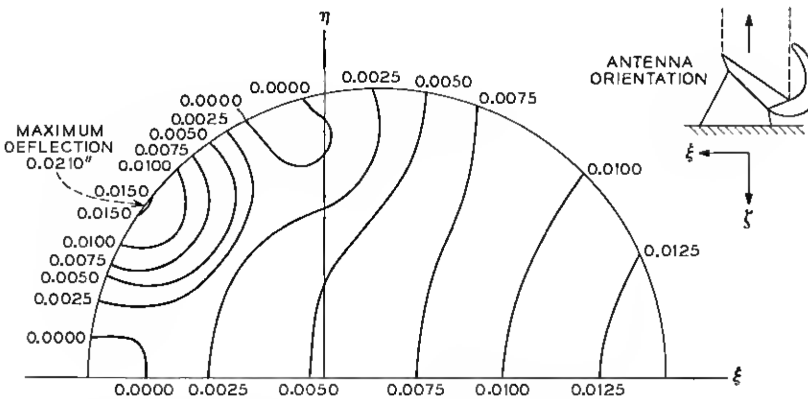

Fig. 8 — Deflections of the main reflector surface in the ζ direction due to gravity loading (deflections in inches).

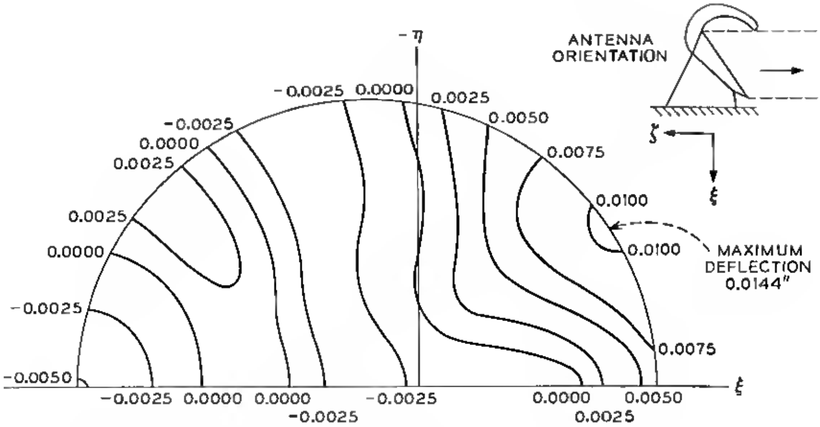

Fig. 9 — Deflections of the main reflector surface in the ζ direction due to gravity loading (deflections in inches).

but still be as light as possible due to its location in the structure. Many of the preliminary concepts studied provided adequate translational rigidity but were weak in torsion about an axis parallel to the axis of the antenna aperture. The structure shown in the figures overcomes this problem, but is considerably heavier than originally anticipated. It weighs about 6½ tons, exclusive of the subreflector.

Regardless of the structural complications introduced by the need to support the subreflector at the edge of the main reflector and the unavoidable compliance of such a geometry, the absolute deflections of the subreflector caused by gravity and a steady wind are reasonably small. Representative values for these deflections in the zenith looking position due to gravity alone are shown in Table I. The coordinate system is the same as that shown in Fig. 8. The right hand screw rule determines the sense of the rotations. The wind deflections of the subreflector must also be considered. Moments about the base of the subreflector support structure induced by a steady 40-mph horizontal wind were also estimated. The wind direction relative to the antenna is the same as used above for the calculation of surface deflections. These moments were reduced to equivalent static loads by the procedure outlined earlier in connection with the main reflector surface. The absolute deflections of the subreflector due to this wind loading in the zenith looking position are also shown in Table I. These values include the effect of simultaneous wind loading on the main reflector surface.

TABLE I
DEFLECTIONS OF THE SUBREFLECTOR IN THE ZENITH LOOKING POSITION

Deflection or Rotation	Gravity	40 mph Steady Wind 60° Aspect Angle
Δ_ξ	$+3.9 \times 10^{-2}$ in.	$+2.0 \times 10^{-2}$ in.
Δ_η	0	$+1.1 \times 10^{-3}$ in.
Δ_ζ	$+2.3 \times 10^{-2}$ in.	$+9.0 \times 10^{-3}$ in.
θ_ξ	0	-1.99×10^{-5} rad.
θ_η	-2.7×10^{-6} rad.	$+1.20 \times 10^{-7}$ rad.
θ_ζ	0	$+1.00 \times 10^{-4}$ rad.

2.3 *Bearings and Azimuth Pedestal*

The slant axis bearing requirements are not significantly different than those for the azimuth bearing except that a smaller load is carried by the slant axis thrust bearing, and a component of the gravity load is continually applied to the slant-axis radial bearing. The wheel and track bearing is a relatively inexpensive and reliable low-friction device for large diameter applications and would be well suited for the open cassegrain antenna. Commercially available roller bearings are expected to meet the requirements for the radial bearing on each axis. The trucks of the slant axis bearing may be recessed into the back-up structure in order to keep the center of gravity of the upper structure as low as possible. Air-gap labyrinth seals are expected to provide environmental protection for both thrust bearings.

The structural function of tbe azimuth pedestal is to transmit the loads from the slant axis bearings to the azimuth axis bearings. As shown (Fig. 2), this can be done in a straightforward manner by means of a robust primary structure connecting the two bearing circles, together with an appropriate secondary stiffener system. The conical surfaces support tbe radial bearings in a natural way. Especially heavy members are used to carry the gravity component acting on the slant axis radial bearing directly to the azimuth trucks. Tbe azimuth radial bearing is supported by a diaphragm which connects it laterally to the azimuth pedestal structure, and by the cone upon wbich it rests. The cone improves the structural integrity and increases the inherent rigidity of the azimutb pedestal.

2.4 *Reflector Alignment*

The main reflector surface may have to be adjusted to bring all points on its surface within acceptable tolerances. An optical align-

ment procedure is practical for this purpose. Such a procedure was used at Andover, Maine to adjust the reflector surface to within a one-sigma value of 0.060″. A relatively simple computer program reduced observed data and calculated the necessary adjustments at the points of support.

Alignment would require favorable weather conditions, and would probably be carried out at night to eliminate solar effects. Under severe conditions it may be necessary to provide a temporary shelter to protect the structure during alignment. An air-supported fabric structure might be considered for this application. Such a shelter could be relatively inexpensive, especially if amortized over a number of antenna installations.

III. ENVIRONMENTAL CONSIDERATIONS

3.1 *Wind Effects*

The effects of wind on an exposed antenna must be considered from the standpoint of:

(1.) Wind induced tracking error and loss of antenna gain under operational wind conditions.

(2.) Structural loading under operating and extreme or "survival" wind conditions.

(3.) Antenna overturning stability under survival wind conditions.

In most cases, the requirement for extreme structural rigidity in antenna design is the controlling factor and stress levels under the most severe operating conditions seldom become critical. An exception to this rule is the main reflector panels where the wind loading situation must be carefully considered. Section 2.2 presents the surface deflections due to a typical wind load distribution.

Wind induced deflections of the reflector surface and subreflector support structure produce pointing errors and a decrease in gain due to defocusing. These effects are of a random nature. Consequently, the structure must be designed to limit the gain reduction to a fraction of a db and the variation in pointing direction to a small fraction of the antenna beamwidth.

In addition to the pointing error due to structural deformation, an error is caused by the dynamic wind-induced torque about the antenna rotational axes. The magnitude of this torque is given by

$$T_w(t) = C_w V(t)^2$$

where $V(t)$ is the wind speed, a function of time

C_w is an experimentally determined wind torque coefficient in units of foot-pounds/(miles per bour)^2.

C_w has been experimentally determined for the open cassegrain antenna as a function of wind azimuth aspect angle and slant axis rotation angle by an extensive series of hydrodynamic tests on scale models of the antenna. Details of these tests are reported elsewhere.[4]

The minimum azimuth stall torque due to wind loading has been estimated to occur at a horizontal wind velocity of 71 mph. This situation would occur under the conditions of a slant axis angle of 45° and a wind aspect angle of 270°, as defined in Fig. 10. This estimate is based on the use of drive gear ratios which permit acceptable tracking rates for near-zenith missions, and the use of two 25-hp hydraulic azimuth drive units.

For the consideration of items (1.) and (2.) above, wind moment

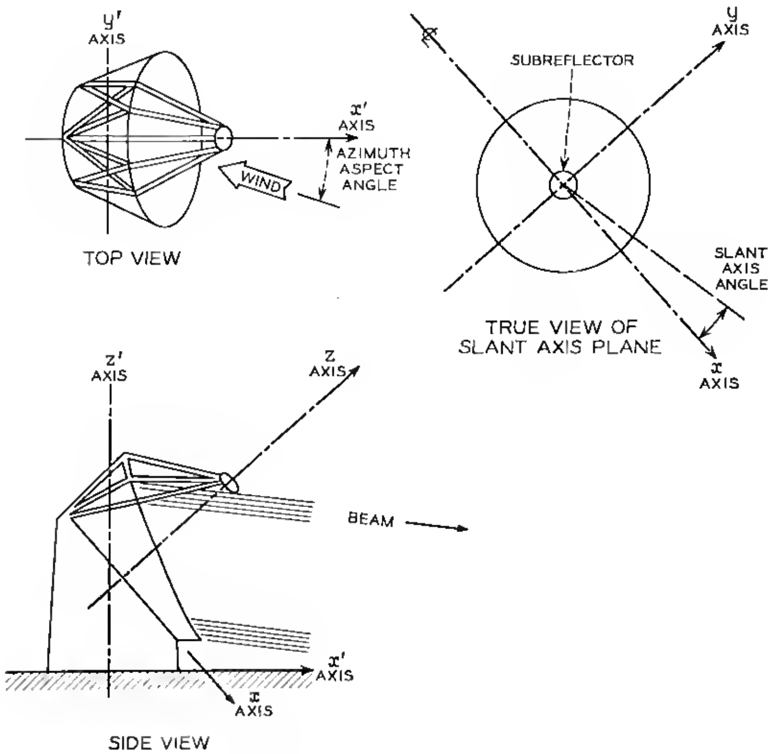

Fig. 10 — Orientation of axis of rotation (zero slant axis angle shown).

coefficients have been experimentally determined for pairs of axes in the planes of the slant and azimuth thrust bearings. The dynamic components of bearing and structural loading are calculated on the basis of these coefficients and the total drag coefficient. Table II exhibits maximum values of these coefficients obtained by hydrodynamic model tests from Ref. 4. These values indicate that the wind overturning moments at 100 mph are much less than the stability moments based upon the estimated weight and location of the center of gravity of the antenna. These conclusions support the contention that the open cassegrain is suitable for exposed operation.

The feasibility of friction drives for the two antenna axes has been investigated. Such drive systems would lead to reductions in cost and weight. However, such systems appear to be marginal in hypothetical worst case situations, with the possibility of slipping under certain circumstances. Hence, conventional ring-and-pinion gear drives are recommended for both axes. By mounting the slant-axis bull gear on the upper rotating structure, with the drive pinion on the azimuth pedestal, the necessity of carrying power beyond the slant axis bearing can be avoided.

3.2 *Thermal Effects*

A large structure exposed to full solar radiation may experience considerable distortion as portions of the structure are shadowed. If reflective paint finishes cannot be made to adequately minimize thermal deflections throughout the structure, especially in the long columns supporting the subreflector, it may be necessary to provide compensating mechanisms to maintain the required precision.

TABLE II

(ANGLES AS DEFINED IN FIG. 10)

Torque Axis	Maximum Wind Coefficient Ft-lbs/(mph)^2	Slant Axis Angle	Wind Azimuth Aspect Angle
* Vertical axis z'	58	45°	270°
* Slant axis z	12	135°	315°
Slant bearing axis x	56	135°	270°
Slant bearing axis y	40	180°	0°
Azimuth bearing axis x'	92	45°	90°
Azimuth bearing axis y'	160	0	0

* Determine drive torque requirements.

3.3 *Precipitation and Icing*

The geographical location of the antenna site will determine to a great extent the problems which must be faced to achieve reliable all-weather operation. The effects of snow and ice accumulation may have to be considered for most locations.

The steep incline of the main reflector surfaces at all pointing attitudes provides an inherent snow-shedding feature. It is proposed to fabricate the reflector surface of thin stretch-formed aluminum panels, which would make it practical to heat the rear of the panels to melt snow and ice accumulations. If electrical heating is used for this purpose, it has been estimated that a 250-kw capacity would be required to keep the reflector surface clear under nominal conditions. Surface treatment of panels and structure with anti-sticking flourocarbon resins may also be practical to minimize collection of ice and snow.

IV. CONCLUSIONS

It makes sense to think of the possibilities of using monocoque or semi-monocoque construction techniques for certain portions of the structure. Since the configuration of each component of the antenna can be described in terms of surfaces, there is no reason why portions of structural shells might not be suitable. This is particularly true of the azimuth pedestal and the conical surfaces supporting the radial bearings. Numerical analysis routines soon will be available to study such components.

Since the deflection patterns of the main reflector surface and the motion of the subreflector under various loading conditions are actually inputs to determine the decrease in system performance in terms of electrical parameters, it follows that the final mechanical criterion is based on electrical response characteristics. Hence it may be possible to formulate such a criterion directly and dispense with the obsolute tolerances on surface run-out, etc. that normally provide the standards for the mechanical designer. For example, deflections of the subreflector along the axis of the feed horn are much less severe than transverse displacements of the subreflector in terms of pattern degradation and tracking jitter. Also, surface deflections should be judged in terms of an auxiliary "best-fit" paraboloid which has its focal point coincident with the design paraboloid, rather than by reference to the original design paraboloid itself. All this suggests it would be meaningful to consider a structural optimization study in which the structure is designed on the basis of desired electrical performance rather than deflection tolerances.

Considerable future work must be done on the dynamic response characteristics of the open cassegrain configuration. In addition to the determination of natural frequencies and normal modes as inputs for control system design, the response of the structure to the random wind loading must be examined. The nature of the loading suggests that statistical variables might be very useful for such a description. There are few discussions of this type of structural response available in the literature. Those that appear are limited to the design of earthquake sensitive structures. An undertaking of this sort would be a prodigious effort, but might be extremely useful in the discussion of the behavior of exposed deflection-sensitive structures.

The various analyses conducted to date have demonstrated the mechanical feasibility of the open cassegrain configuration. The preliminary concept discussed in these pages has been shown to meet the structural requirements that are reasonable to impose at this stage. Detailed analyses have been directed only to certain specific problem areas where an obvious need for first-order quantitative information was recognized. These investigations have shown plausible solutions for such problems are available, and have provided better understanding of the overall structural behavior. In no sense should it be inferred that such calculations represent a design for the open cassegrain. Rather, they establish the configuration shown as a justifiable concept for such an antenna.

V. ACKNOWLEDGMENTS

K. N. Coyne and F. Brauns participated in many aspects of the structural analysis and their assistance proved invaluable. M. Lutchansky was involved in the early phases of the study and many of his ideas are reflected in the final structural configuration. H. W. Boschen demonstrated his skill and ingenuity in building the model of the structure.

REFERENCES

1. Nelsou, W. L., and Cole, J. W., Autotrack Control Systems for Antenna Mounts with Non-Orthogonal Axes, B.S.T.J., this issue, pp. 1367–1403.
2. Gallagher, R. H., *A Correlation Study of Methods of Matrix Structural Analysis*, New York, The MacMillan Company, 1964.
3. Przemieniecki, J. S., Matrix Structural Analysis of Substructures, AIAA Journal, *1*, No. 1, Jan. 1963.
4. Coyne, K. N., Hydrodynamic Techniques for Study of Wind Effects on Antenna Structures, B.S.T.J., this issue, pp. 1339–1365.